NAVAL HEALTH RESEARCH CENTER

QUANTITATIVE EEG ANALYSIS OF

SLEEP CHRONOPHYSIOLOGY:

A COMPARISON BETWEEN ROOT MEAN SQUARE (RMS)

ESTIMATION AND FAST FOURIER TRANSFORMATION (FFT)

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Summary

<u>Problem.</u>

Few formal comparisons between fast Fourier transform (FFT) and digital period-amplitude (DPA) analyses of all-night electroencephalographic (EEG) data have been reported. However, the uses of both approaches have been reported widely in the sleep literature.

<u>Objectives.</u>

We sought to quantitatively model the temporal dynamics of sleep EEG using FFT and DPA derivations of spectral estimates applied to the same set of raw data, then to determine the degree of statistical similarity or difference between the two sets of results.

<u>Approach.</u>

Sleep EEG data (C3-A2 lead, 272 samples/sec, band-passed at 0.5-70 Hz) from eleven, normal, male subjects (23-41 yr) were acquired from the second of three nights spent in the laboratory. The raw data were subjected to an FFT and combined into delta, theta, alpha, sigma, and beta bands and 30-second epochs. This produced band-specific estimates of signal power. The DPA data reduction was accomplished by finding the half-wave peak voltage of the band-pass filtered signal between zero crossings, calculating its band mean for the 30-second epoch and dividing the band mean by the square root of 2. This gave band-specific root mean square (RMS) estimates of signal amplitude (the square root of power). Epochs containing artifact were identified visually and not used. Three-minute epochs were created from the means of 30-second epochs. The Spearman rank-correlation coefficient was calculated within bands and within subjects for each of the FFT and DPA 3-minute epochs. A 5-level (bands) Friedman non-parametric 1-way analysis of variance was calculated for the correlation coefficients with the null hypothesis of equality of correlation across bands.

<u>Results.</u>

Chronophysiologic dynamics of the EEG appeared qualitatively quite similar, with some minor exceptions, across the two approaches for all five bands. The average correlations for the five bands were .942, .849, .803, .817, and .866, respectively. The Friedman statistic was highly significant. Post hoc analysis showed the correlation within the delta band to be significantly higher than within the theta, alpha and sigma bands. Temporal reciprocity across the night between delta and beta patterns was quite evident in both the FFT and DPA data.

<u>Conclusions.</u>

The two different derivations of spectral estimates of a sleep EEG signal, FFT and DPA, provided highly similar qualitative and quantitative results. The finding of an inverse temporal relationship between delta and beta activities with both approaches replicated a similar finding reported by another laboratory. The inter-method reliability of the two approaches supported the usefulness of quantitative analyses of sleep EEG data.
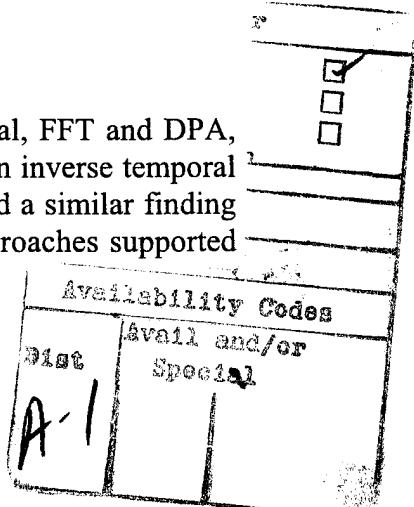
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Quantitative EEG Analysis of Sleep Chronophysiology:
A Comparison Between Root Mean Square (RMS)
Estimation and Fast Fourier Transformation (FFT)

There still is no standardized methodology for the application of quantitative electroencephalographic (QEEG) techniques in sleep research Hasten (1985)   Computer programs for data collection and analysis vary from one sleep laboratory to the next, sometimes making between-laboratory comparisons a difficult process Karacan (1978). Hoffman (1979) states that the development of new laboratory procedures (i.e. automated QEEG analysis) should be accompanied by some careful, formal discussion of the procedures. The logical "next step" should then involve a formal comparison and evaluation of the results these procedures yield. However to date, few sleep researchers have conducted direct empirical or statistical evaluations between readily available QEEG methodologies Pigeau (1981).

During the past 30 years of sleep research, specific efforts have been directed towards developing automated methodologies to quantify nocturnal EEG data Agnew (1967); Armitage (1989); Armitage (1992a); Armitage (1992b); Church (1975); Dumermuth (1983): Hoffmann (1984); Johnson (1972); Kapfhammer (1992): Ktonas (1987); Ktonas (1981); Larsen (1992); Terstegge (1993); Uchida (1992a); Uchida (1992b). Much of this work has focused on formulating mathematical models that reliably characterize the two most salient features of sleep EEG (i.e., frequency and amplitude). These various models may describe sleep EEG either in the *time-domain* (i.e., amplitude fluctuations as a function of time), or in the *frequency-domain* (i.e. amplitude fluctuations as a function of frequency).

At present, two prominent methods of QEEG analysis are power spectral analysis, usually accomplished by fast Fourier transformations (FFT), and digital period-amplitude (DPA) analysis. FFT have been applied to frequency domain EEG data to model cortical activity during particular times or stages of sleep (e.g., REM or slow-wave sleep) Larsen (1992; Terstegge (1993). Dumermuth (1983) applied FFT to and computed power spectra for all-night sleep EEG (frequency-domain modeling). Several methods of DPA analysis (e.g., full-wave zero-cross, half-wave zero-cross, first derivative) have been formulated and applied to sleep EEG data to characterize amplitude changes, within specified frequency bands, across an entire night sleep (Church (1975) Feinberg (1978), Armitage (1992a) Feinberg (1980) Armitage (1992b) Uchida (1992a) Uchida (1992b) reported the first substantial study of DPA in all-night EEG. Hoffmann (1984) used the results of DPA to assess the overlap in variance between conventional stage scoring and the quantification of tonic EEG activity and found significant agreement between

DPA and stage scores. In most of these studies the focus has been on describing one specific QEEG methodology (i.e., FFT or DPA) and either its application to polysomnography or how it compares to conventional stage scoring. Very few formal comparisons have been done directly between FFT and DPA analyses with respect to all-night EEG Pigeau (1981).

Some important preliminary work has been published and should be noted. Ktonas (1981) applied both FFT and DPA (half-wave zero-cross), as well as visual analysis, to short segments of analog prefiltered EEG data displaying predominantly delta wave forms. The objective of that study was not to perform a statistical analysis between methods on the delta band proper, but to provide methodological insight. These authors state that if DPA is used to average individual wave periods and peak amplitudes over a given time window of narrowband EEG, DPA and FFT can be expected to yield similar results. Recent evidence suggests this may not always be so. Uchida (1992b) reported a discrepancy between the FFT-analyzed delta-beta sleep EEG dynamics and DPA-analyzed delta-beta dynamics published by Armitage (1992a). Whereas Uchida (1992b) reported delta (0.3-3 Hz) and beta (20-28 Hz) to oscillate inversely across REM/NREM sleep, Armitage (1992a) found delta (0.5-4 Hz) and beta (16-32 Hz) to oscillate in phase across the sleep. In an attempt to resolve the discrepancy, Uchida (1992b) applied DPA to their data and found similar results to those yielded by the FFT. The matter remains unresolved.

We now report a statistical comparison between two methods of quantitative EEG analysis: the FFT and spectral power estimation via a DPA root mean square (RMS) estimator using a commercially available system now routinely used in our laboratory. The RMS estimate is the square root of the variance or power of a signal Cooper (1980). Additionally, we present representative data in a manner similar to a recent report of an apparent systematic and cyclical inverse relation between slow and fast EEG frequencies throughout nocturnal sleep Uchida (1992b).

METHOD
Subjects
The data for this study were derived from eleven male control subjects (age range = 23 - 41 years, mean = 29.7 ± 5.98 years, median = 30 years) who had participated in a study of the fatigue and sleep disturbances in HIV-infected individuals. These subjects spent three consecutive nights (an adaptation night, a baseline night and a third night involving blood sampling) in one of two identically equipped sleep research labs (one located at The Scripps Research Institute, La Jolla, CA. and the other located at Balboa Naval Hospital, San Diego, CA). All subjects were

medically fit, did not suffer from any primary sleep disorder and were free of any major psychopathology.

Polysomnographic Equipment

Both sleep labs were equipped with identical instrumentation for paperless recording and automated processing of polysomnographic data. Sleep electrophysiology was recorded using the Nicolet Ultrasom™ (Madison, WI) recording system. This commercially available system includes the following hardware and software: a SUN 386i UNIX computer work station, Ultrasom™ V2.1 sleep recording and analysis software, several utility programs for quantitative EEG signal analyses, a built-in 12-bit analog-to-digital converter, and a 32 channel Nicolet (Model SM2000) analog amplifier. For all EEG signals, low and high frequency analog filters were set at 0.5 and 70 Hz, respectively, full-scale sensitivity was set at 500 µV. All channels were sampled and preprocessed (including filtering) at 272 Hz; subsequently the data samples were low-pass filtered to prevent aliasing and stored at 68 Hz for post processing. The system was calibrated using a 1 Hz/100 µV sine wave. Signals were digitized, analyzed and stored to hard disk on-line. After final processing was completed, all raw data and analysis results were archived to optical disk for permanent storage. For a complete technical description of the data acquisition system see Kap (1991).

Procedure

For the present analysis, only the second (baseline) night was used. Gold-plated (Grass) electrodes were fixed with collodion at the following electrode positions according to the international 10-20 system: Fp1, Fp2, Fz, Cz, Pz, P3, C3, C4, T3, T4, O1, O2, Pg1, Pg2. All EEG channels were referenced to linked ears (A1/A2). In addition to EEG, two electrooculogram (EOG) channels, chin electromyogram (EMG) and electrocardiogram (EKG) were also recorded. Time in bed was approximately 8 hours (2200 h - 0600 h)

Visual Analysis. The Ultrasom™ system displays up to 16 channels per bed on a color monitor and mimics the appearance of an analog EEG signal written to paper. Technicians can then scroll through the sleep record and perform conventional visual analysis. Manual scoring of sleep stages was done according to criteria defined by Rechtschaffen and Kales (1968), based on 30-second epochs. Any epochs containing activity that might disrupt quantitative EEG (movement or momentary arousals) were eliminated from subsequent analysis.

Quantitative EEG Analysis. All quantitative EEG analyses were performed using data recorded from the left central (C3) site. The two methods of quantitative EEG analysis evaluated here

were: fast Fourier transformation (FFT) and root mean square (RMS) estimation. Our objective was to apply both QEEG methodologies independently, and describe the similarities and differences between both quantitative models for analyzing human EEG during sleep.

Ultrasom™ V2.1 software calculates and stores a root mean square (RMS) estimate (on-line during data acquisition) for each 30-second epoch for each of the five conventional EEG bands: delta (.5-4 Hz); theta (4-8 Hz); alpha (8-12 Hz); sigma (12-16 Hz), and beta (16-32 Hz). The Ultrasom™ system initially used a standard FFT to transform raw EEG data into the frequency domain. Adaptive center-frequency bandfiltering was then performed with respect to the classical EEG bands. An all-inclusive set of filters were used so no data were lost. The spectral data in each band was then transformed back and DC filtered to allow for pattern detection and amplitude estimation in the time domain. Computation of the RMS estimator for each band assumed the resultant time-domain band passed signals were zero mean (DC filtered) and sinusoidal (narrow band). The DPA data reduction was accomplished by finding the half-wave peak voltage of the band-pass filtered signal between zero crossings, calculating its band mean for the 30-second epoch and dividing the band mean by the square root of 2. This gave band-specific root mean square (RMS) estimates of signal amplitude (the square root of power). An important feature of the Ultrasom™ approach was the adaptive center frequency band filtering within the context of the conventional EEG bands. The center frequency of the filter adapted to the peak frequency of the dominant activity in that band.

An FFT was performed on the raw EEG data following the routine provided in Press (1986). The algorithm was written in UNIX-based C programming language and took approximately 5-6 hours to process an 8-hour sleep record. The FFT was done using the same five conventional frequency bands as above.

Statistical Analysis.

Since all-night EEG measures do not always satisfy normality assumptions, non-parametric statistical procedures were employed in the present analysis. Epochs either visually scored as movement or displaying any artifact were eliminated and data were smoothed over six epochs (3 minutes) using a moving average. For each subject and within each frequency band, a Spearman Rank correlation coefficient was computed between RMS and FFT values. Following computation, a Friedman non-parametric one-way ANOVA was done on the correlation coefficients using the BMDP 3S non-parametric statistical routines. Frequency band was treated as a 5-level repeated measure variable and the hypothesis of equality of correlations (between RMS and FFT estimates) across frequency bands was proposed.

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RESULTS

The temporal dynamics and estimations of spectral power in an all-night sleep EEG could be successfully tracked using either the FFT-based method or the RMS estimator. Fig. 1 shows such all-night tracking within the five conventional sleep frequency bands (i.e. delta, theta, alpha, sigma, beta), for a representative subject (S10). The near coincidence of the estimations of spectral power in the delta frequency (0.5 - 4 Hz) is evident in the overlapping solid (FFT) and broken (RMS) lines (Spearman correlation = 0.947, $p < 0.0001$). The estimations for other frequencies are noted to be similarly coincident. See Figure 1 (next page).

Table 1 contains the intrasubject Spearman rank correlation coefficients between FFT-based and RMS spectral power estimates for each of the five standard sleep frequency bands for all

TABLE 1. Spearman rank correlation coefficients between FFT and RMS (root mean square) power spectral estimates*.

Subject	Delta	Theta	Alpha	Sigma	Beta
S1	.968	.927	.89	.858	.945
S2	.957	.836	.886	.883	.906
S3	.948	.635	.821	.897	.919
S4	.962	.925	.852	.855	.806
S5	.883	.801	.756	.804	.872
S6	.937	.819	.73	.773	.871
S7	.929	.855	.699	.742	.897
S8	.961	.904	.743	.842	.768
S9	.933	.894	.877	.666	.733
S10	.947	.852	.701	.854	.912
S11	.937	.892	.881	.815	.896

* all correlations are significant at $p < 0.0001$.

subjects (n=11). These values displayed a high degree of similarity indicating very similar assessments of the temporal fluctuations in power across the five conventional sleep frequency bands. The high correlations for delta frequency activity and fairly high correlations for all the other frequencies (range 0.635 - 0.968, all significant at $p < 0.0001$) should be noted. The average (n=11) correlations for delta, theta, alpha, sigma and beta activity were: 0.942, 0.849, 0.803, 0.817, 0.866, respectively. The omnibus Friedman ANOVA was significant ($c_r^2 = 28.58$, $p < 0.0001$). Post-hoc analysis for the Friedman ANOVA (z-test) indicates the correlation for delta activity was better than that of the other frequencies (all significant at $p < 0.05$) with the

A

DELTA ACTIVITY

B

THETA ACTIVITY

C

ALPHA ACTIVITY

D

**SIGMA ACTIVITY**

E

BETA ACTIVITY
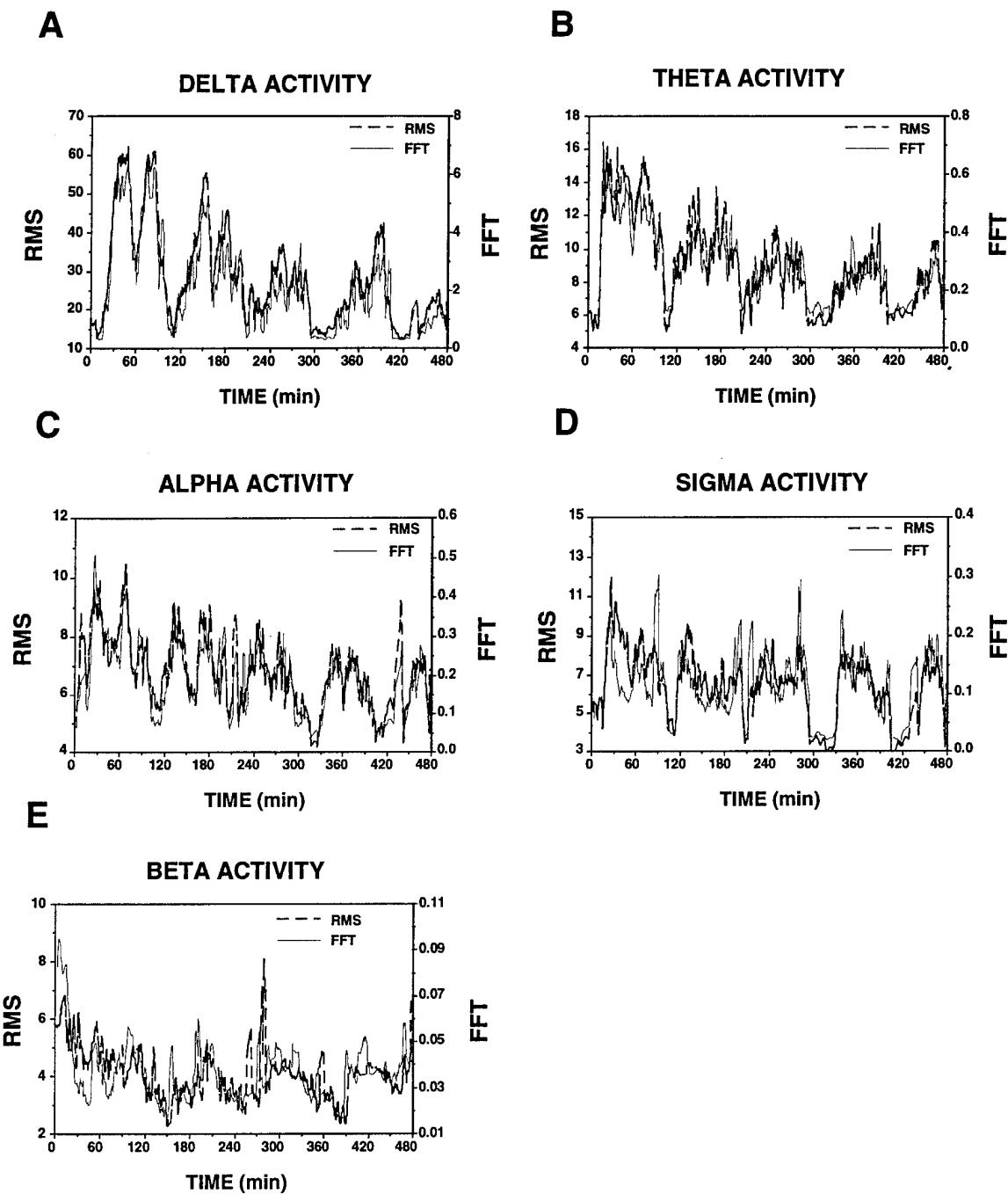
Fig. 1 The five bivariate (double y-axis) plots graphically display one night of polysomnographic data for one subject (S7), derived from the C3 electrode site. The estimation of sleep EEG spectral power can be successfully tracked using either the classical FFT-based analysis or the root mean square estimator. The ordinates were scaled to make the peak power estimates coincide. Units for the left (RMS) and right (FFT) ordinates are: μV, micro-volts, and $\mu V^2/Hz$, microvolts squared per Hertz, respectively. Figs 1A through 1E display, respectively, the all-night spectral power trends within the following frequency bands: Delta (0.5-4 Hz), Theta (4-8 Hz), Alpha (8-12 Hz), Sigma (12-16), Beta (16-32 Hz).

exception of beta. This finding is evident from inspection of the values where the set of correlations for delta power (range = .883 - .968) was notably greater than for the other frequencies (range = .635 - .945).

Fig. 2 (next page) shows four plots where, at certain rare periods, markedly discrepant estimates are apparent. In these graphs, the RMS and FFT time series data were scaled so as to allow the peaks to approximately match. Figs 2A and 2B exemplify intrasubject discrepancies (S6) within the delta and theta frequency bands. In Fig 2A, several peak power estimates (labeled #1, #2, #4) are coincident, but there appear to be two specific time intervals (#3, approx. 170-240 min and #5 approx. 270-390 min.) during which the RMS estimates are greater relative to the FFT-based estimates. For the same subject, theta power is plotted in Fig 2B. At the time periods labeled #1 and #2 and in contrast to Fig 2A, the FFT estimates are notably greater relative to the RMS values. Figs 2C and 2D show similar discrepancies for two separate subjects and frequency bands. Fig 2C, two peak power estimates for delta power are coincident, but during the time intervals labeled #1 (210-270 min.) and #2 (380-410 min.), the RMS gives higher estimates of power than the FFT. Similarly, Fig. 2D (label #1) shows an instance of an intrasubject discrepancy in the power estimates in the sigma frequency (12-16 Hz). Here a much shorter time period is evident during which the RMS values are much larger relative to the FFT values. Visual inspection of the raw EEG waveforms show that the time period displaying this discrepancy (90-110 min.) include multiple sleep spindles of mean frequencies slightly greater than 12.0 Hz.

The overall power trends of different frequency bands of the sleep EEG were plotted together to show the interrelationships over time (Fig. 3). In a manner similar to previously published work Armitage (1992a; Uchida 1992a), we present figures based on a three minute moving average of standard scores (z-scores), with shading to demarcate manually scored REM/ NREM periods. In Fig. 3A the dynamic inverse relationship between delta and beta power, as given by an FFT, is evident. A similar reciprocal relationship is disclosed using the RMS estimator (Fig. 3B). This result is consistent with data recently published by Uchida (1992b). Delta and beta EEG power oscillated reciprocally across non-REM and REM sleep.
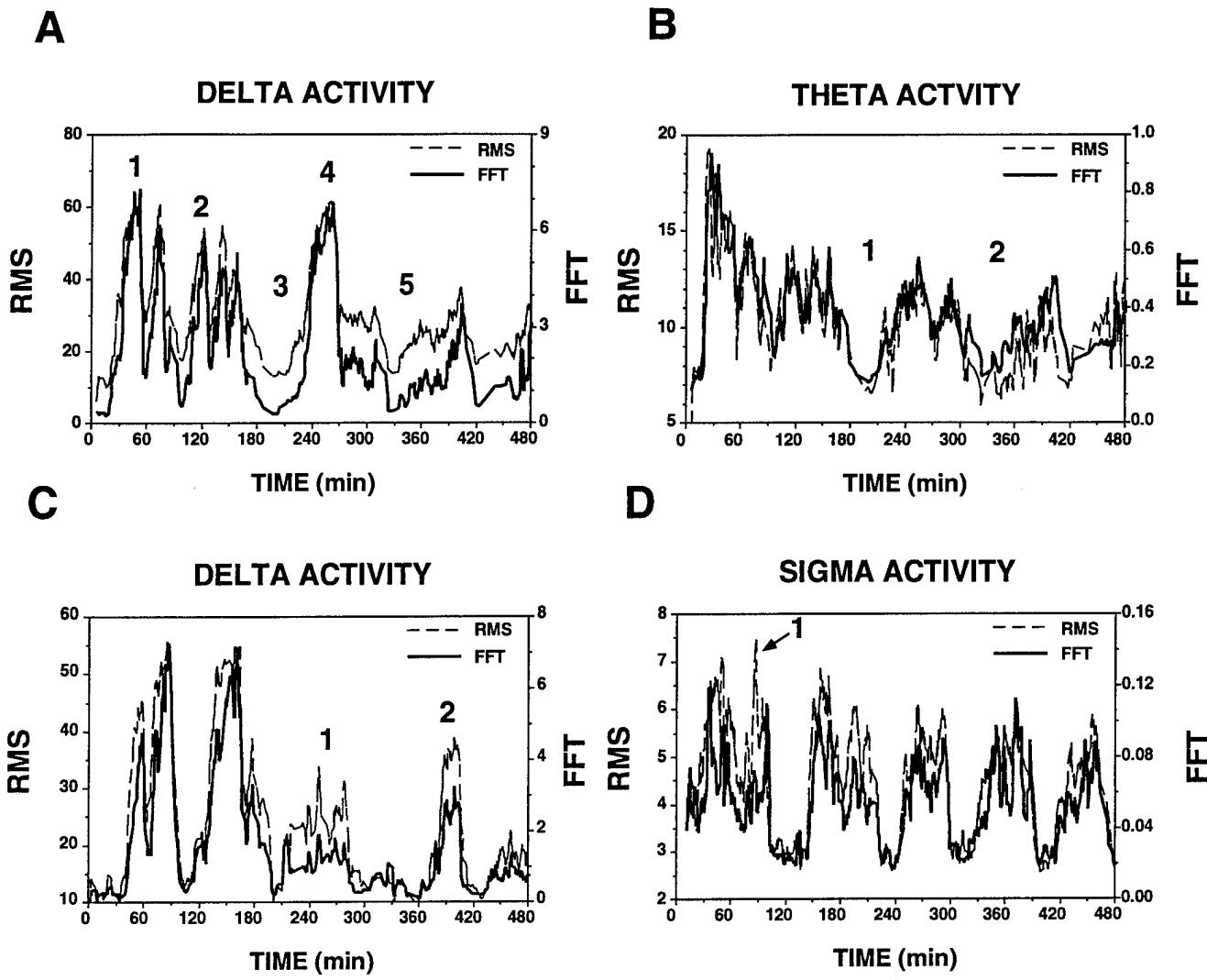
FIG.2. Four bivariate (double y-axis) plots showing, at certain time periods (numerically labeled), discrepant estimates in spectral power. Units for the left (RMS) and right (FFT) ordinates are: μV, microvolts, and $\mu V2/Hz$, microvolts squared per Hertz, respectively. (A) Plot of delta (0.5-4 Hz) activity for one subject (S4). Labels #1,#2,#4 show coincident peak power estimates. Time periods marked #3 and #5 show time periods where RMS estimates are markedly greater relative to the FFT spectral estimates. (B) Plot of theta activity for same subject (S4) where, in contrast, FFT estimates are greater relative to the RMS spectral estimates. It should be noted that the time intervals labeled #3 and #5 in Fig. 2A coincide with the time intervals labeled #1 and #2 in Fig. 2B. (C) Plot of delta activity for another subject (S2) showing coincidence in peak power estimates and marked differences in delta power estimation at times labeled #1 and #2. (D) Plot of sigma (12-16 Hz) activity for subject S8 showing a brief time period (labeled #1) where there is a marked increase in the RMS estimate relative to the FFT spectral estimates. Analysis of the raw EEG waveforms during this time reveal multiple sleep spindles of mean frequency greater than 12.0 Hz.

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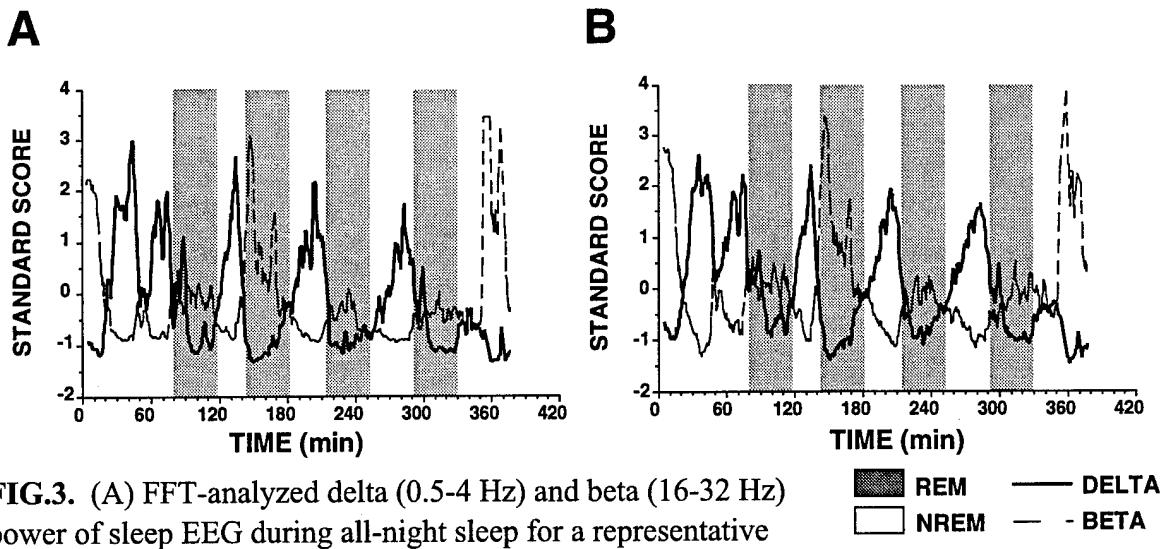
FIG.3. (A) FFT-analyzed delta (0.5-4 Hz) and beta (16-32 Hz) power of sleep EEG during all-night sleep for a representative subject (S11). The interrelated dynamics of delta and beta power are shown as systematic and cyclic variations across the night. Beta and delta power oscillate reciprocally across REM/NREM sleep. (B) The same inverse relation between delta (0.5-4 Hz) and beta (16-32 Hz) is shown using the RMS estimator.

Discussion

The application of quantitative methods to the analysis of sleep EEG impacts the assessment of sleep by shifting the focus from visually and identifiable features reflecting phasic EEG events (e.g., sleep spindles, K-complexes) to fluctuations in background tonic activity that may reflect biological processes. Such quantitative approaches may allow better correlation with other shifting biological variables, such as core body temperature or levels of endogenous sleep related substances, than would correlation with numbers of phasic events or discontinuous sleep staging systems. The quantitative analysis of the sleep EEG time series data is dependent on the use of some method of spectral estimation. In the present study, two methods for spectral estimation, a fast Fourier transformation (FFT) and a digital-period-amplitude (DPA) root mean square (RMS) estimate of spectral power, were compared.

The FFT and RMS methods showed similar patterns of variation over time and similar abilities to demonstrate the NREM and REM sleep transitions evident in marked changes of amplitude within frequency bands. The observation of an inverse relationship between delta and beta power replicated the observation of Uchida (1992b) and extended their observation by showing that the RMS estimate detects this relationship. That FFT, other period analysis Hoffmann (1984) and the RMS estimate all showed this identical

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relationship suggests that these methods can be compared in terms of their ability to model the temporal dynamics, within specified frequencies, of sleep EEG.

The RMS method of estimation used by the commercially available Ultrasom™ software used adaptive center frequency bandfiltering and amplitude quantification in the time domain while the FFT method did not. This has important implications for the comparison between methods. RMS amplitude quantification in the time domain allows a better distinction between tonic background activity, patterns, and artifacts within the same frequency band. The adaptive filtering meant that the RMS bandwidths had some flexibility not present with the fixed predefined bandwidths used with the FFT method. The RMS estimator found the peak of the activity within the frequency range of interest (e.g., delta) but used a filter centered on that peak. This feature pertained to all frequency bands. The filter slopes for subsequent bands overlap such that the overall gain is 1 for the full frequency range. This flexibility is consistent with a model of EEG activity postulating that various frequencies of activities represent classes of events. For example, alpha frequency reactivity to light may be considered an alpha event whether the mean frequency is in the middle of the alpha band at 10.0 Hz or is slower at 8.5 Hz. In this model, rather than artificially inflating the amplitude estimates of adjacent frequency bands just because the center of activity within the band of interest happens to veer too closely to the adjacent band, the exact slopes of filtering for each band window are adjusted to account for the actual spectral peak within the band margin.

The adaptive filtering of the Ultrasom™ is probably one cause of discrepancies in spectral estimates using the RMS and FFT methods. Hence, inspection of the data in the higher frequency bands for the discrepancies noted in Fig. 2D are consistent with the observation of periodic sleep spindles with frequencies slightly greater than 12.0 Hz. The bandwidth contributed by these spindles includes both alpha and sigma activity by fixed bandwidths but was included solely as sigma activity by the RMS estimator. The periods of discrepancy of delta activity showing the RMS estimates relatively greater to the FFT estimates (Fig. 2A) also showed that, within the theta range (Fig. 2B), the FFT estimates were relatively greater than the RMS estimates during these same time periods. These data suggested that activity with a frequency peak in the higher delta range was attributed solely to delta by the RMS estimator but was divided between delta and theta by the FFT estimator. For the periods of slow wave sleep where delta activity was clearly contained solely within the delta range (e.g. peak frequency at 1-2 Hz) both estimators were strongly coincident. These data suggest that the high correlation observed between methods, despite the added feature of adaptive center frequencies incorporated into the RMS estimator, probably underestimates the agreement between the two methods. We

conclude that the RMS method does not produce unacceptably different QEEG results from those obtained by the FFT method.

Finally, the quantitative nature of RMS data has facilitated the development of databases comparing the strength and dynamic interaction of different frequency components over time in normal subjects as well in neurological or psychiatric patient populations. These data also lend themselves to topographical mapping of patterns of activity distribution thus allowing characterization of regional cortical function and dysfunction through the different sleep stages over time.

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13. ABSTRACT (Maximum 200 words)

Two quantitative electroencephalographic (QEEG) techniques, fast fourier transformations (FFTs) and spectral power estimation using root mean square (RMS), were applied to all night EEG recordings from 11 normal subjects. The results were compared statistically to determine the degree of similarity between them. Both QEEG techniques yielded very comparable chronophysiological models of Sleep EEG, with the highest correlation (mean = 0.947) for the delta frequency (0.5-4 Hz) and fairly high correlations for all other frequencies. The inverse relationship between delta and beta power, previously reported using the digital period analysis and FFT, is now replicated using the RMS method. It appears that the adaptive filtering used by the Nicolet Ultrasom^{TM} (Madison, WS) recording system in relation to the RMS analysis was the main cause of the discrepancies between the two spectral estimate techniques. These results indicate that different automated QEEG techniques can produce comparable sleep EEG models, allowing for reliable interlaboratory comparisons.

14. SUBJECT TERMS Sleep Quantitative Electroencephalography (QEEG), Fast Fourier transformations (FFT), Root Mean Square (RMS), Delta, Beta.

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